

Possible signatures of unparticles in rare annihilation type B decays

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Abstract

We investigate the effect of unparticles in the pure annihilation type decays $B^- \rightarrow D_s^- \phi$ and $D_s^- K^{*0}$. Since these decays have only annihilation contributions their branching ratios are expected to be very small in the standard model and the direct CP asymmetry parameters to be zero. We find that due to the unparticle effect these branching ratios can be significantly enhanced from their standard model values. Furthermore, sizable nonzero direct CP violation could also be possible in these channels due to the presence of intrinsic CP conserving phase in the unparticle propagator.

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There are many discrete massive particles in reality which can exist in a scale non-invariant theory as in the case of the standard model (SM) whereas, in a scale invariant theory, in four space-time dimensions, the mass spectrum of fields is continuous or zero. Recently, Goergi [1] suggested that there could be a possibility that the scale invariant sector (termed as unparticle) indeed exists but might have been undetected so far as the intermediate particles mediating these two sectors are believed to be very heavy. The standard model fields might be scale invariant at high energy but scale invariance might have been broken somewhere above the electroweak scale. However, here the SM is taken to be scale non-invariant all the way up to high energy.

Now let us consider a scenario in which there exist the scale invariant sector with non-trivial infrared fixed point at high energy, which is represented by the Banks-Zaks (\mathcal{BZ}) fields [2], and also the SM fields. Thus, the high energy theory contains both the SM fields and the \mathcal{BZ} fields, which interact via the exchange of particles of mass $M_{\mathcal{U}}$ with the generic form

$$\frac{1}{M_{\mathcal{U}}^k} O_{SM} O_{\mathcal{BZ}} ,$$

where O_{SM} is the operator of mass dimension d_{SM} and $O_{\mathcal{BZ}}$ is the operator of mass dimension $d_{\mathcal{BZ}}$ made out of SM and \mathcal{BZ} fields, respectively. The couplings of the \mathcal{BZ} fields cause dimensional transmutation and below the scale $\Lambda_{\mathcal{U}}$ the \mathcal{BZ} operators match onto the unparticle operators leading to the interaction between the SM and the Unparticle sector of the type

$$C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{\mathcal{BZ}} - d_{\mathcal{U}}}}{M_{\mathcal{U}}^k} O_{SM} O_{\mathcal{U}} ,$$

where $C_{\mathcal{U}}$ is a coefficient in the low energy effective theory and $O_{\mathcal{U}}$ is the unparticle operator with scaling dimension $d_{\mathcal{U}}$. Furthermore, $M_{\mathcal{U}}$ should be large enough such that its coupling to the SM fields must be sufficiently weak, consistent with the current experimental data.

Unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a non-integral number $d_{\mathcal{U}}$ of invisible massless particles. Unparticle, if exists, could couple to the standard model fields and consequently affect the low energy dynamics. The effect of unparticle stuff on low energy phenomenology has been extensively explored in Refs. [3, 4, 5, 6].

A clean signal of the unparticle stuff can be inferred from various analyses, e.g., the missing energy distribution in mono-photon production via $e^-e^+ \rightarrow \gamma \mathcal{U}$ at LEP2 [3] and

direct CP violation in the pure leptonic $B^\pm \rightarrow l^\pm \nu_l$ modes etc. [5, 6]. In this paper, we would like to see whether the pure annihilation type B decays could provide any interesting avenues to visualize the signatures of unparticles. The decay modes considered here are $B^- \rightarrow D_s^- \phi$ and $D_s^- K^{*0}$ which have only annihilation type contributions in the SM and therefore expected to be very rare. Only the upper limits are known for these channels which are given as $\text{Br}(B^+ \rightarrow D_s^+ \phi) < 1.9 \times 10^{-6}$ and $\text{Br}(B^+ \rightarrow D_s^+ \bar{K}^{*0}) < 4 \times 10^{-4}$ [7]. Furthermore, since the decay amplitudes of these modes have contributions arising only from annihilation diagrams, the direct CP asymmetry parameters in these modes are identically zero. Although some new physics (NP) models like two Higgs doublet model and R-parity violating supersymmetric model can provide new contributions to these channels and thereby open up the possibility of observing direct CP violation [8]. But, if the strong phases in the SM and NP amplitudes turn out to be tiny, CP violation cannot be observed even if there is new physics contribution to the decay amplitudes. However, if the new contributions to the decay amplitudes are due to the unparticles, which contain the new CP conserving phase coming from the unparticle propagators, CP violation could be observed even for vanishing SM strong phase. In this paper we would like to explore such a possibility.

The decay modes considered here are $B^- \rightarrow D_s^- \phi$ and $D_s^- K^{*0}$ which arise in the standard model from the tree level annihilation diagrams. The b and \bar{u} quarks of the initial B meson annihilate to a W^- boson which subsequently hadronises to the final D_s^- and $\phi(K^{*0})$ mesons. The effective Hamiltonian describing such transitions is given as

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* \left[C_1(\mu) \bar{q}_\alpha \gamma_\mu (1 - \gamma_5) c_\alpha \bar{u}_\beta \gamma^\mu (1 - \gamma_5) b_\beta + C_2(\mu) \bar{q}_\beta \gamma_\mu (1 - \gamma_5) c_\alpha \bar{u}_\alpha \gamma^\mu (1 - \gamma_5) b_\beta \right], \quad (1)$$

where $C_{1,2}$ are the Wilson coefficients, α and β are the color indices, $q = s(d)$ for the final state meson $\phi(K^{*0})$. Thus one can obtain the transition amplitude for these processes as

$$A(B^-(p_B) \rightarrow D_s^-(p_D) V(p_V, \epsilon)) = \frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* a_1 X, \quad (2)$$

where V denotes the final vector meson ϕ/K^{*0} , $a_1 = C_1 + C_2/N_c$ and $X = \langle D_s^- V | \bar{q} \gamma^\mu (1 - \gamma_5) c \bar{u} \gamma_\mu (1 - \gamma_5) b | B^- \rangle$ is the matrix element of the four quark current operators between the initial and final mesons. The evaluation of this hadronic matrix element is not possible from the first principles of QCD and one requires some additional assumptions to determine it. Since, in this paper, we are interested to see the effect of unparticles in the

CP violation asymmetries, we will not pay much attention for its evaluation. However, if one resorts to the generalized factorization approach then one can factorize this matrix element as $X = \langle D_s V | (\bar{q}c)_{V-A} (\bar{u}b)_{V-A} | B^- \rangle \equiv \langle D_s V | (\bar{q}c)_{V-A} | 0 \rangle \langle 0 | (\bar{u}b)_{V-A} | B^- \rangle$. The first element can be related to its corresponding crossed channel as $\langle D_s(p_D) V(p_V, \epsilon) | (\bar{q}c)_{V-A} | 0 \rangle \equiv \langle V(p_V, \epsilon) | (\bar{q}c)_{V-A} | D_s(-p_D) \rangle$. Using Lorentz invariance, these matrix elements can be represented in terms of form factors and decay constants, as defined in [9]. Thus one can obtain the transition amplitude as

$$A(B^-(p_B) \rightarrow D_s^-(p_D) V(p_V, \epsilon)) = -\frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* a_1 f_B 2m_V (\epsilon^* \cdot p_D) A_0(p_B^2). \quad (3)$$

The corresponding branching ratio is given as

$$\text{Br}(B^- \rightarrow D_s^- V) = \frac{p_c^3}{8\pi m_V^2} |A(B^- \rightarrow D_s V) / (\epsilon^* \cdot p_D)|^2, \quad (4)$$

where p_c is the c.o.m. momentum of the emitted particles in the B rest frame.

Now we would like to see how unparticle stuff will affect the transition amplitudes. Here, we assume that the charged unparticles mediate the interaction between the initial and final mesons. The possible existence of charged unparticles and their consequences have been recently discussed in Refs. [5, 6]. It is well known that, depending on the nature of the original \mathcal{BZ} operator $O_{\mathcal{BZ}}$ and the transmutation, the resulting unparticle may have different Lorentz structure. In our analysis, we consider only the scalar and vector type unparticles. The coupling of these unparticles to quarks is given as

$$\frac{c_S^{q'q}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{q}' \gamma_\mu (1 - \gamma_5) q \partial^\mu O_{\mathcal{U}} + \frac{c_V^{q'q}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{q}' \gamma_\mu (1 - \gamma_5) q O_{\mathcal{U}}^\mu + h.c., \quad (5)$$

where $O_{\mathcal{U}}$ and $O_{\mathcal{U}}^\mu$ denote the scalar and vector unparticle fields and $c_{S,V}^{q'q}$ are the dimensionless coefficients which in general depend on different flavors and are assumed to be real. For the charged unparticle exchange, q' in Eq (5) belongs to the up quark sector (u, c, t) and q to the down type quarks (d, s, b).

The propagator for the scalar unparticle field is given as [1, 3]

$$\int d^4 x e^{iP \cdot x} \langle 0 | T O_{\mathcal{U}}(x) O_{\mathcal{U}}(0) | 0 \rangle = i \frac{A_{d_{\mathcal{U}}}}{2 \sin d_{\mathcal{U}} \pi} \frac{1}{(P^2 + i\epsilon)^{2-d_{\mathcal{U}}}} e^{-i\phi_{\mathcal{U}}}, \quad (6)$$

where

$$A_{d_{\mathcal{U}}} = \frac{16\pi^{5/2}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}} + 1/2)}{\Gamma(d_{\mathcal{U}} - 1)\Gamma(2d_{\mathcal{U}})}, \quad \text{and} \quad \phi_{\mathcal{U}} = (d_{\mathcal{U}} - 2)\pi. \quad (7)$$

Similarly, the propagator for the vector unparticle is given by

$$\int d^4x e^{iP \cdot x} \langle 0 | T O_{\mathcal{U}}^\mu(x) O_{\mathcal{U}}^\nu(0) | 0 \rangle = i \frac{A_{d_{\mathcal{U}}}}{2 \sin d_{\mathcal{U}} \pi} \frac{-g^{\mu\nu} + P^\mu P^\nu / P^2}{(P^2 + i\epsilon)^{2-d_{\mathcal{U}}}} e^{-i\phi_{\mathcal{U}}} . \quad (8)$$

The interesting thing in these propagators is the presence of the new CP conserving phase $\phi_{\mathcal{U}}$, which leads to a spectacular interference pattern and hence can exhibit nonzero direct CP violating effects in many rare decay channels. Here it should be noted that the vector unparticle will not contribute to the decay channels considered here. This is because, the contraction of P_μ arising from axial coupling i.e., $\langle 0 | A_\mu | B^- \rangle$ with the $(-g^{\mu\nu} + P^\mu P^\nu / P^2)$ term in the vector unparticle propagator gives vanishing contribution, while the vector coupling $\langle 0 | V_\mu | B^- \rangle$ is identically zero. Therefore, only scalar type unparticles will contribute to these rare decay modes. Thus, the contributions arising from scalar unparticle exchange is given as

$$A^{\mathcal{U}}(B^- \rightarrow D_s^- V) = \frac{\lambda}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \frac{A_{d_{\mathcal{U}}}}{2 \sin(d_{\mathcal{U}} \pi)} (m_B^2)^{d_{\mathcal{U}}-1} e^{-i\phi_{\mathcal{U}}} X , \quad (9)$$

where $\lambda = (c_S^{ub} c_S^{cq})$ and X is the hadronic matrix element. Now, including the unparticle contributions, one can write the transition amplitude as

$$A^T(B^-(p_B) \rightarrow D_s^-(p_D) V(p_V, \epsilon)) = A^{\text{SM}}(1 + r e^{i(\gamma - \phi_{\mathcal{U}})}) , \quad (10)$$

where γ is the weak phase of SM amplitude i.e., we have used $V_{ub} = |V_{ub}| e^{-i\gamma}$. Furthermore, r denotes the magnitude of the ratio of unparticle to SM amplitude and is given as

$$r = \frac{\lambda}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \frac{A_{d_{\mathcal{U}}}}{\sqrt{2} \sin(d_{\mathcal{U}} \pi)} \frac{(m_B^2)^{d_{\mathcal{U}}-1}}{G_F |V_{ub} V_{cq}^*| a_1} . \quad (11)$$

Thus, we obtain the CP averaged branching ratio $\langle \text{Br} \rangle \equiv [\text{Br}(B^- \rightarrow D_s^- V) + \text{Br}(B^+ \rightarrow D_s^+ V)]/2$, including the unparticle contributions, as

$$\langle \text{Br} \rangle = \text{Br}^{\text{SM}}(1 + r^2 + 2r \cos \gamma \cos \phi_{\mathcal{U}}) , \quad (12)$$

where Br^{SM} is the SM branching ratio. It should be noted that since the direct CP violation in these modes is zero in the SM, the SM CP averaged branching ratio is same as $\text{Br}(B^- \rightarrow D_s^- V)$. The direct CP violation parameter, which is related to the difference of the partial decay rates, given as

$$\begin{aligned} A_{CP} &= \frac{\Gamma(B^- \rightarrow D_s^- V) - \Gamma(B^+ \rightarrow D_s^+ \bar{V})}{\Gamma(B^- \rightarrow D_s^- V) + \Gamma(B^+ \rightarrow D_s^+ \bar{V})} \\ &= \frac{2r \sin \gamma \sin \phi_{\mathcal{U}}}{1 + r^2 + 2r \cos \gamma \cos \phi_{\mathcal{U}}} . \end{aligned} \quad (13)$$

We now proceed to evaluate the SM branching ratios using the QCD factorization approach. Although the QCD factorization predictions for annihilation contributions suffer from end point divergences, and therefore have large uncertainties, but one can still have an estimate on the order of the branching ratios. In this approach, the annihilation amplitudes are parameterized as [10]

$$A(B^- \rightarrow D_s^- V) = i \frac{G_F}{\sqrt{2}} V_{ub} V_{cq}^* f_B f_{D_s} f_V b_2(D_s, V), \quad (14)$$

where $b_2 = C_F C_2 A_1^i / N_c^2$, with $C_F = 4/3$ as the color factor and N_c is the number of colors. A_1^i is given as

$$A_1^i \approx 6\pi\alpha_s \left[3 \left(X_A - 4 + \frac{\pi^2}{3} \right) + r_\chi^{D_s} r_\chi^V (X_A^2 - 2X_A) \right], \quad (15)$$

where

$$r_\chi^{D_s} = \frac{2m_{D_s}^2}{m_b(m_c + m_s)}, \quad r_\chi^V = \frac{2m_V}{m_b} \frac{f_V^\perp}{f_V}. \quad (16)$$

X_A denotes the end point divergences which can be parameterized as

$$X_A = (1 + \rho_A e^{i\phi_A}) \ln \left(\frac{m_B}{\Lambda_h} \right), \quad \text{with} \quad \Lambda_h = 0.5 \text{ GeV}. \quad (17)$$

For the numerical evaluation, we use the particle masses, lifetime of B^- meson and the CKM elements $V_{ub} = (3.96 \pm 0.09) \times 10^{-3}$, $V_{cs} = 0.97296 \pm 0.00024$, $V_{cd} = 0.2271 \pm 0.0010$ from [7]. The decay constants (in GeV) as $f_{D_s} = 0.294$ [7], $f_\phi = 0.237$ [11], $f_B = 0.2$, $f_{K^*} = 0.218$, $f_V^\perp = 0.175$ [10], the current quark masses (in GeV) as $m_b = 4.2$, $m_c = 1.3$, $m_s = 0.08$ [10]. We use $C_2 = -0.295$ [12] evaluated at $m_b/2$ scale at next-to-leading order, $\rho_A = 1$ and $\phi_A = -20^\circ$ [10] for the annihilation parameters. Thus we obtain the branching ratios as

$$\begin{aligned} \text{Br}^{\text{SM}}(B^- \rightarrow D_s^- \phi) &\approx (4.2 \pm 0.2) \times 10^{-7}, \\ \text{Br}^{\text{SM}}(B^- \rightarrow D_s^- K^{*0}) &\approx (1.2 \pm 0.1) \times 10^{-8}, \end{aligned} \quad (18)$$

which are well below the present upper limits and are also consistent with the results of PQCD calculation $\text{Br}(B^+ \rightarrow D_s^+ \phi) = 3.0 \times 10^{-7}$ [11] and $\text{Br}(B^+ \rightarrow D_s^+ K^{*0}) = (1.8 \pm 0.3) \times 10^{-7}$ [13].

Now we proceed to see the effect of unparticle stuff on the branching ratios and CP violation parameters. As seen from Eq.(9), the unparticle contribution contains three unknown parameters, namely, the dimension of the unparticle fields $d_{\mathcal{U}}$, the energy scale $\Lambda_{\mathcal{U}}$ and the coupling λ . Therefore, to see the effect of unparticles we fix the energy scale as $\Lambda_{\mathcal{U}} = 1$

TeV. Now using the CKM angle $\gamma = 70^\circ$ we show in figures 1 and 2, the variations of the branching ratios and CP violation parameters with d_U for different values of λ . From the figures we can see that when the scale dimension d_U is less than 1.4, the branching ratios are very sensitive to it and above $d_U = 1.4$ the unparticle contributions are negligible and the branching ratio curves converge to the corresponding SM values. Furthermore, one can also obtain significant direct CP asymmetries due to the unparticle contributions. As seen from the figures, when the coupling $\lambda \approx \mathcal{O}(1)$, maximum CP violation i.e., up to 50% (70%) is possible for the $B^- \rightarrow D_s^- \phi$ ($B^- \rightarrow D_s^- K^{*0}$) channels. These CP violation parameters are also quite sensitive to the scale dimension d_U and above $d_U \approx 1.6$ they approach to zero, which is the corresponding SM value.

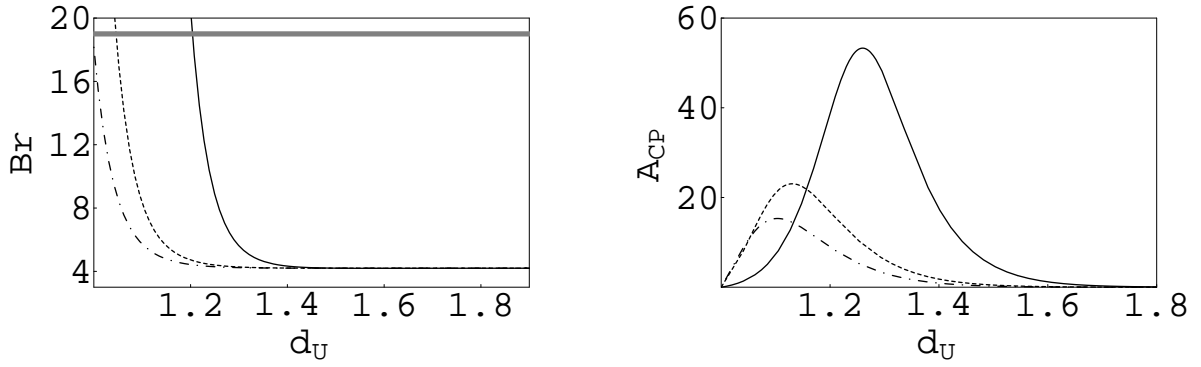


FIG. 1: CP averaged branching ratio $\langle \text{Br} \rangle$ (in units of 10^{-7}) and CP violation parameter (in %) for the decay mode $B^- \rightarrow D_s^- \phi$, where the solid, dashed and dot-dashed lines correspond to $\lambda=1, 0.1$ and 0.05 respectively. The horizontal thick line in the branching ratio plot represents the experimental upper limit.

Unparticle physics associated with a hidden scale invariant sector at a higher energy scale with a nontrivial fixed point has received significant attention in a short span of time. Many interesting unparticle specific signatures have been pointed out. In this work, we have explored another situation where we can expect clean unparticle signatures. We have studied the phenomenology of unparticle physics in the rare B decay channels $B^- \rightarrow D_s^- \phi$ ($B^- \rightarrow D_s^- K^{*0}$). Since in the SM these decay modes have only annihilation contribution so the branching ratios are expected to be quite small. These values can be significantly enhanced from their SM values if unparticle effect is taken into account. The direct CP asymmetries for these modes are identically zero in the SM and therefore are very much suitable ones

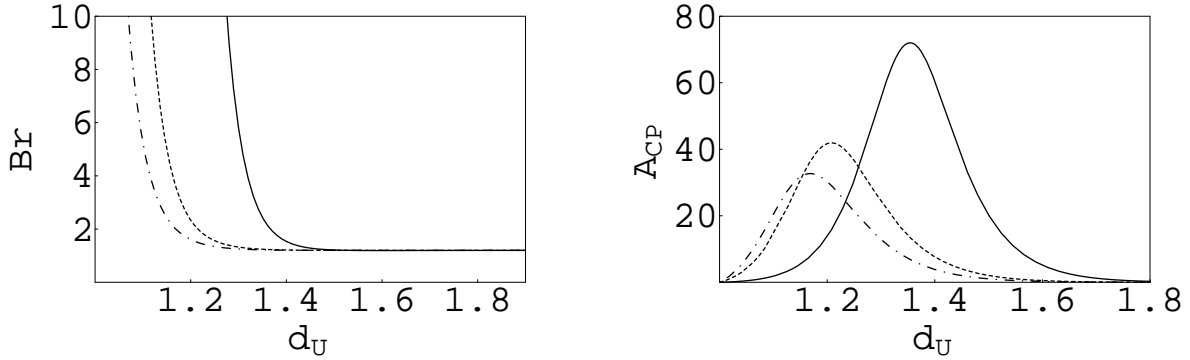


FIG. 2: CP averaged branching ratio $\langle Br \rangle$ (in units of 10^{-8}) and CP violation parameter (in %) for the decay mode $B^- \rightarrow D_s^- K^{*0}$. The solid, dashed and dot-dashed lines correspond to $\lambda=1$, 0.1 and 0.05 respectively.

to look for new physics. Because of the presence of intrinsic CP conserving phase in the unparticle propagator nonzero and sizable direct CP violation can be observed in these modes. To conclude, enhancement in the branching ratios in the rare annihilation type B decays $B^- \rightarrow D_s^- \phi$ ($B^- \rightarrow D_s^- K^{*0}$) and nonzero direct CP violation will be clean signals of new physics and unparticle physics will be a strong contender for the same.

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